Modeling stochastic variability in accreting black holes

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SEVENTH FRAMEWORK PROGRAMME

NARODOWE CENTRUM NAUKI

Chandra X-ray Center

Fermi Gamma-ray Space Telescope

Outline

Introduction / Motivation
Why variability?

Part 1. Stochastic model for the luminosity fluctuations
Kelly et al 2009, 2011, 2014.

Part 2. Applications.

Fermi/LAT γ-ray blazar variability. *Sobolewska et al 2014. ApJ, 786, 143*
Radio-to-γ variability of 3C 273. *Sobolewska et al 2014, in progress*

Summary

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Introduction. Variability

Variability is a probe of astrophysics

Variability properties reflect physics of the variability processes

X-ray variability process is multiplicative (Uttley+2005).

A tool to weigh BHs in AGN (X-rays, McHardy+2006).

Geometry of the X-ray emitting region (Kara+, Alston+, de Marco+).

Blazar emitting region (TeV, Aharonian+2007).

Classification of astronomical sources based on variability, in the era of massive time-domain astronomical surveys

Introduction. Variability

Non-parametric methods (PSD, structure function) suffer from distorting effects (e.g. Vaughan+2003, Emmanoulopoulos+2010) due to:

- the finite sampling of the light curve: red noise leak and aliasing

- irregular and/or sparse sampling

Monte Carlo simulations to calculate the expected periodogram as a function of the true underlying PSD (e.g. Done+1992, Uttley+2002):

- χ^2 minimization based methods

- computationally intensive

Likelihood based approaches
e.g. Kelly+2009, 2011, 2014; Vaughan 2010; Miller+2010

Part 1. Stochastic model for the luminosity fluctuations

Part 1. Stochastic model for the luminosity fluctuations

Advantages of our approach:

Parametrized stochastic process, PSD parameters derived directly from the lightcurve.

No spectral distortions due to irregular/sparse sampling, red noise leak, aliasing because the Fourier transforms are not performed. Model accounts for arbitrary sampling and observation lengths.

Bayesian approach, statistical inference based on **the likelihood function,** i.e., the probability of the measured lightcurve as a function of the PSD parameters.

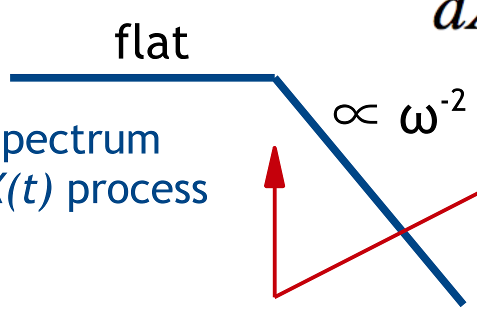
posterior dist. of parameters given the data $\propto$ *Likelihood* $\times$ *prior*

Markov Chain Monte Carlo (MCMC) to sample from the posterior probability distribution for the model parameters, e.g. PSD characteristic timescales.

Part 1. Stochastic model for the luminosity fluctuations

Ornstein-Uhlenbeck process, OU
Continuous time first order autoregressive process, CAR(1)
Damped Random Walk, DRW

$$dX(t) = -\omega_0(X(t) - \mu)dt + \varsigma dW(t), \quad \omega_0, \varsigma > 0$$



power spectrum
of the *X(t)* process

characteristic frequency, ω_0

mean

amplitude of the driving noise

$$P_{\mathrm{OU}}(\omega) = \frac{\varsigma^2}{2\pi} \frac{1}{\omega_0^2 + \omega^2}$$

Kelly+2009

Part 1. Stochastic model for the luminosity fluctuations

Application of the OU model to the optical AGN lightcurves

Kelly+2009: OU model explains the optical AGN lightcurves with an impressive fidelity.

McLeod+2010: OU model used to describe the 10-year SDSS Stripe 82 AGN lightcurves.

Kozłowski+2010: AGN selection based on the variability properties (OGLE).

Investigations into the adequacy of the OU model

Good agreement on timescales well sampled by the data (from months to a few years).

On very short timescales (below a few months) the optical PSD slopes steeper than predicted by the OU process (Mushotzky+2011, Kepler; Zu+2013, OGLE).

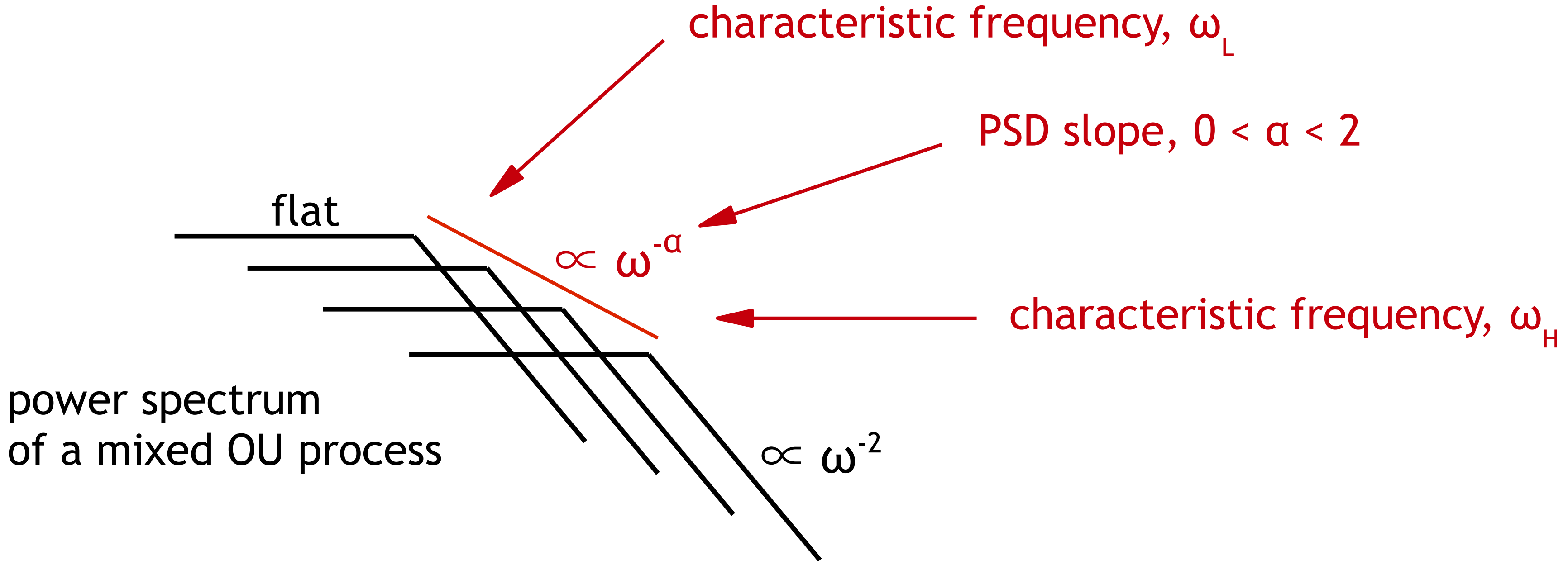
The OU process preferred over several other stochastic and deterministic models (Andrae+2013, SDSS Stripe 82).

OPTICAL

Part 1. Stochastic model for the luminosity fluctuations

X-RAY

Mixed OU process resulting in a PSD with two breaks.



Kelly+2011

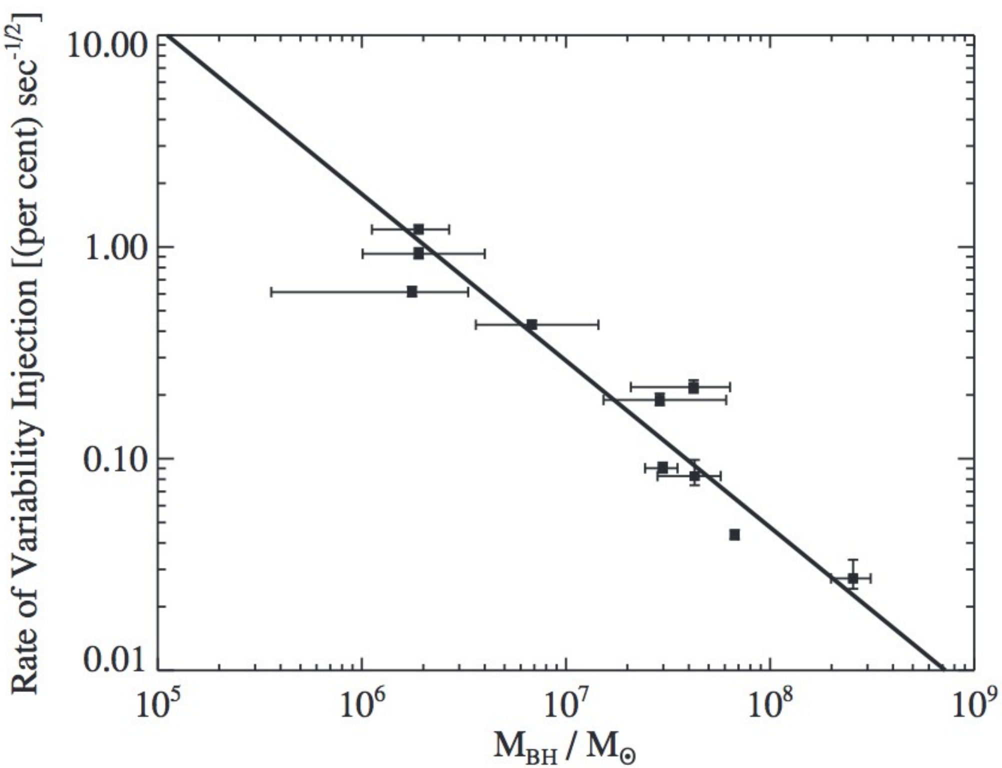
Part 1. Stochastic model for the luminosity fluctuations

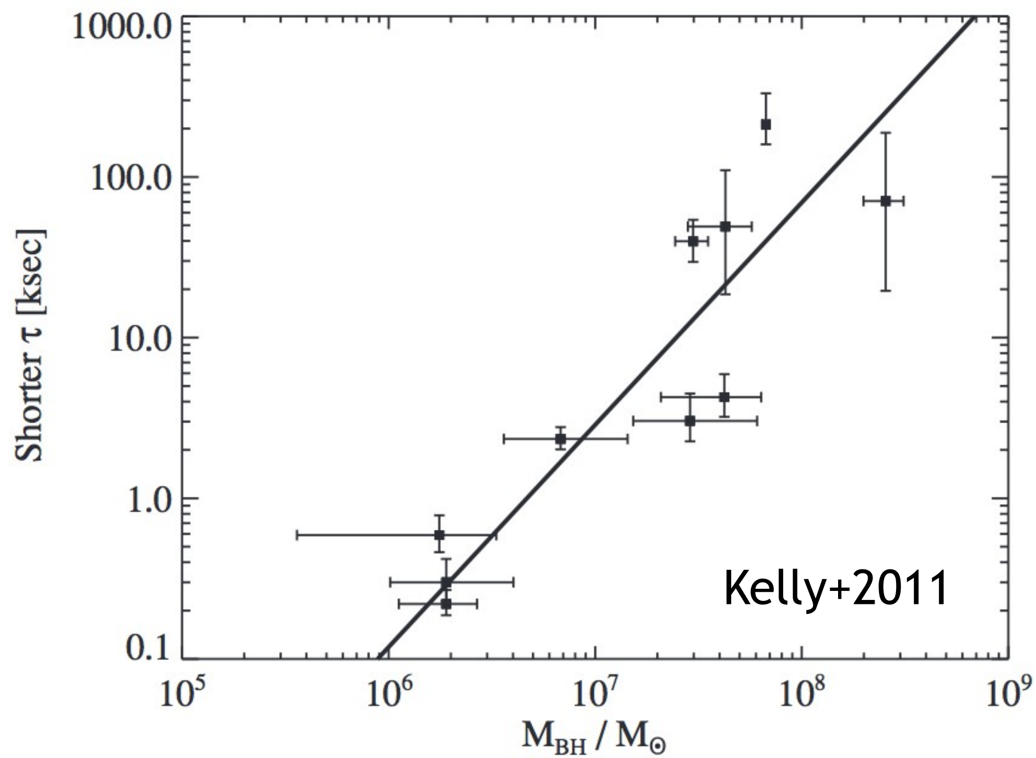
Test on the AGN X-ray data

X-RAY

Successful application of the mixed OU model to the X-ray RXTE (Sobolewska & Papadakis 2009) and XMM-Newton lightcurves of 10 nearby radio-quiet Seyferts.

Potentially the most precise method for estimating the BH mass in AGN, a tight anti-correlation between the amplitude of the driving noise fluctuations and the BH mass.





Part 1. Stochastic model for the luminosity fluctuations

CARMA(p, q)

Continuous time autoregressive moving average process

autoregressive coefficients

AR

$$\frac{d^p y(t)}{dt^p} + \alpha_{p-1}\frac{d^{p-1} y(t)}{dt^{p-1}} + \ldots + \alpha_0 y(t) =$$

$$\beta_q \frac{d^q \epsilon(t)}{dt^q} + \beta_{q-1}\frac{d^{q-1}\epsilon(t)}{dt^{q-1}} + \ldots + \epsilon(t).$$

MA

white noise process

moving average coefficients

Kelly+2014

Part 1. Stochastic model for the luminosity fluctuations

CARMA(p, q)

Continuous time autoregressive moving average process

CARMA(1, 0) = CAR(1)

$$\frac{d^p y(t)}{dt^p} + \alpha_{p-1}\frac{d^{p-1} y(t)}{dt^{p-1}} + \ldots + \alpha_0 y(t) =$$
$$\beta_q \frac{d^q \epsilon(t)}{dt^q} + \beta_{q-1}\frac{d^{q-1}\epsilon(t)}{dt^{q-1}} + \ldots + \epsilon(t).$$

Kelly+2014

Part 1. Stochastic model for the luminosity fluctuations

CARMA(p, q)
Continuous time autoregressive moving average process

Stationary CARMA(p, q) process: $q < p$ and the roots r_k of the AR polynomial have negative real parts

$$A(z) = \sum_{k=0}^{p} \alpha_k z^k$$

PSD of a stationary CARMA(p, q) process is a sum of weighted Lorentzian functions with

centroids	$\propto$	$\lvert \mathrm{Re}(r_k) \rvert$
widths	$\propto$	$\lvert \mathrm{Im}(r_k)/2\pi \rvert$
normalizations	$\propto$	β_i

Kelly+2014

Part 2. Applications

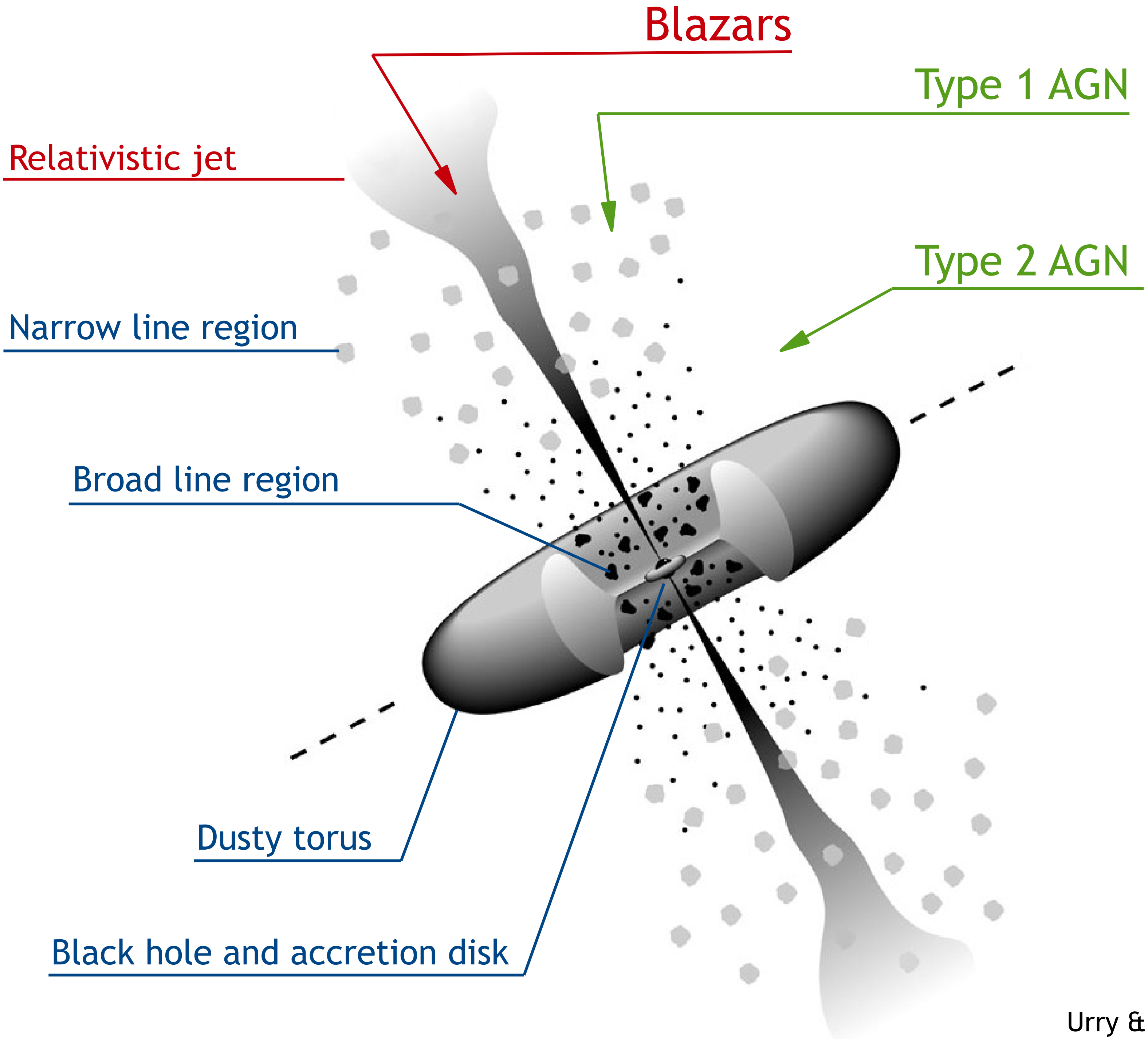
OU/mixed OU process:

Variability of the Fermi/LAT γ-ray blazar lightcurves

CARMA process:

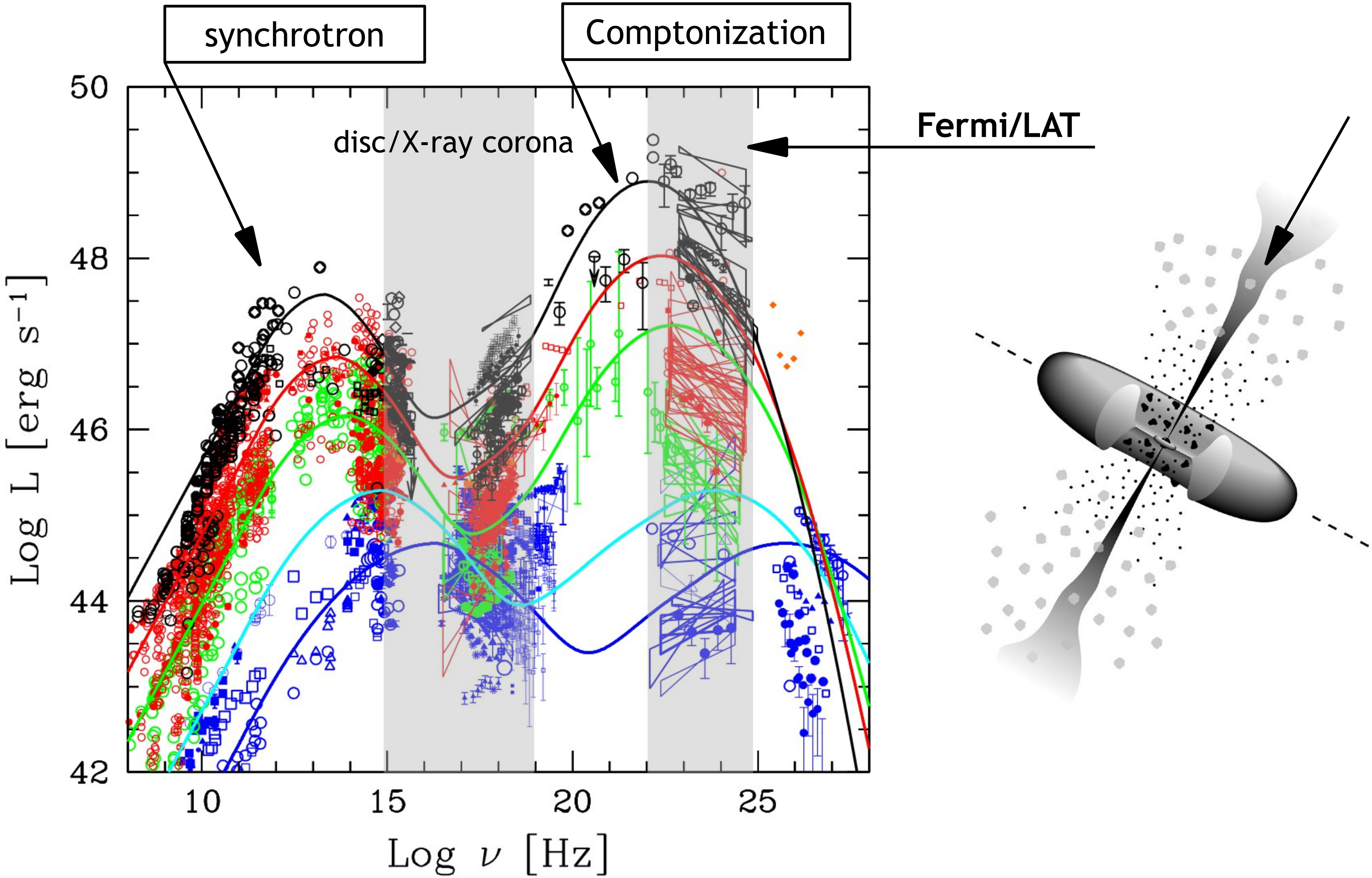
Radio-to-γ variability of 3C 273 (in progress)

Part 2. Applications. Fermi/LAT γ-ray blazars



Urry & Padovani 1995

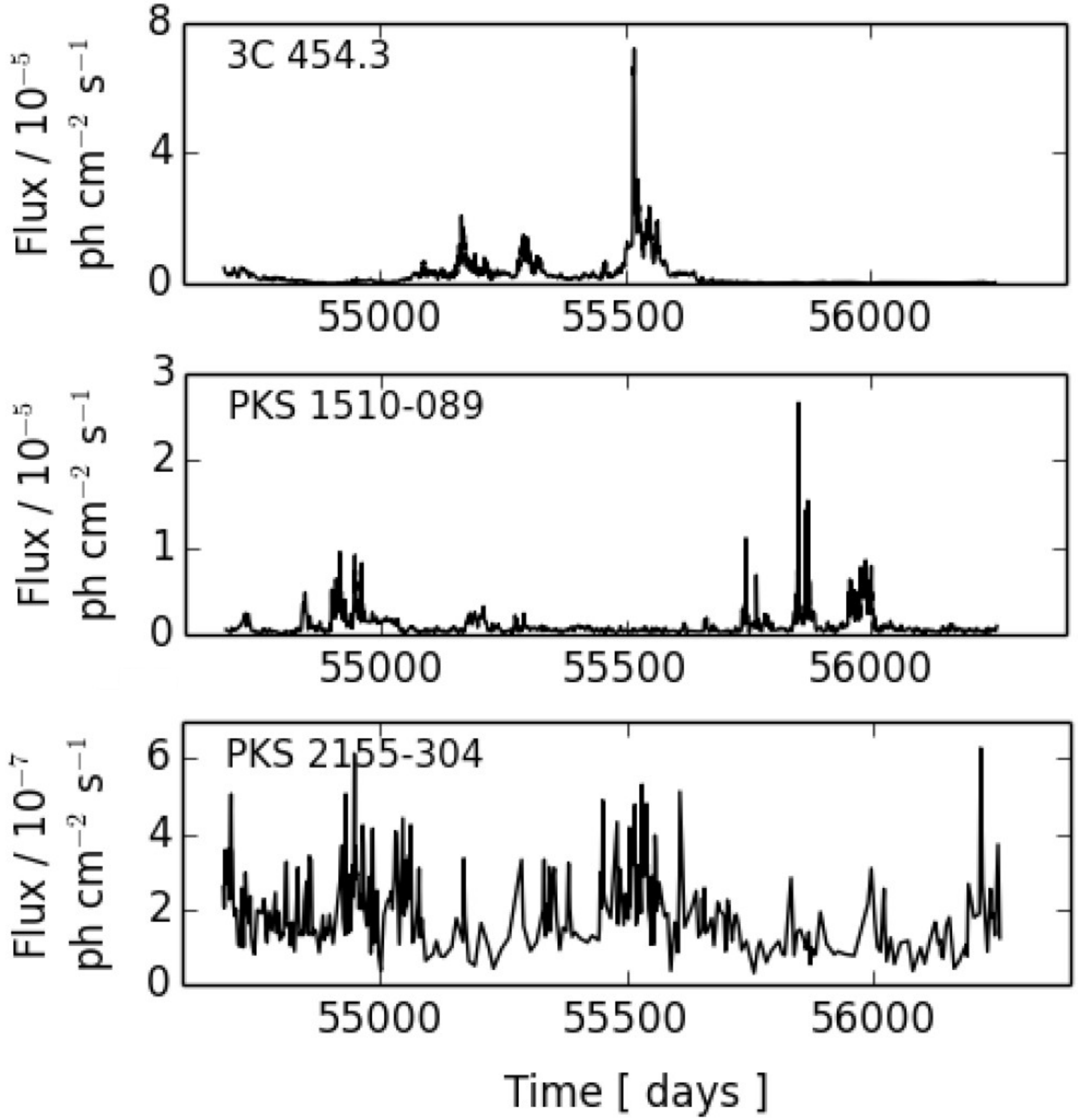
Part 2. Applications. Fermi/LAT γ-ray blazars



Ghisellini 2013 (review)

Part 2. Applications. Fermi/LAT γ-ray blazars

The first 4 years of the Fermi/LAT survey data



Sobolewska+2014

Part 2. Applications. Fermi/LAT γ-ray blazars

Questions

1. Is the γ-ray blazar variability consistent with a stochastic process?

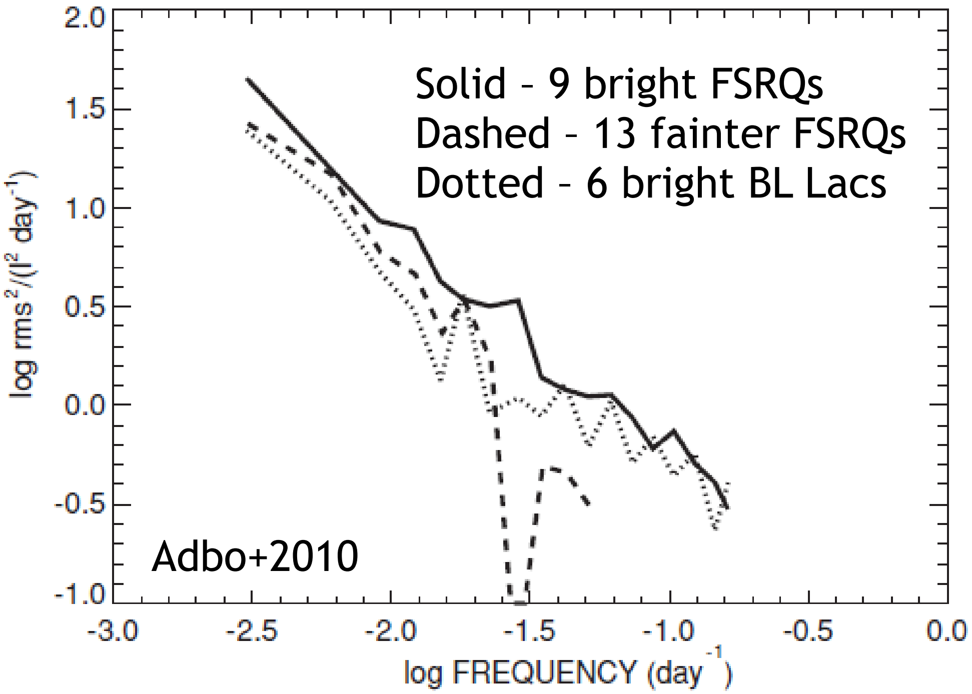
2. Are the 'flares' a signature of an additional variability process?

3. How do the γ-ray blazar variability timescales compare to the X-ray variability timescales?

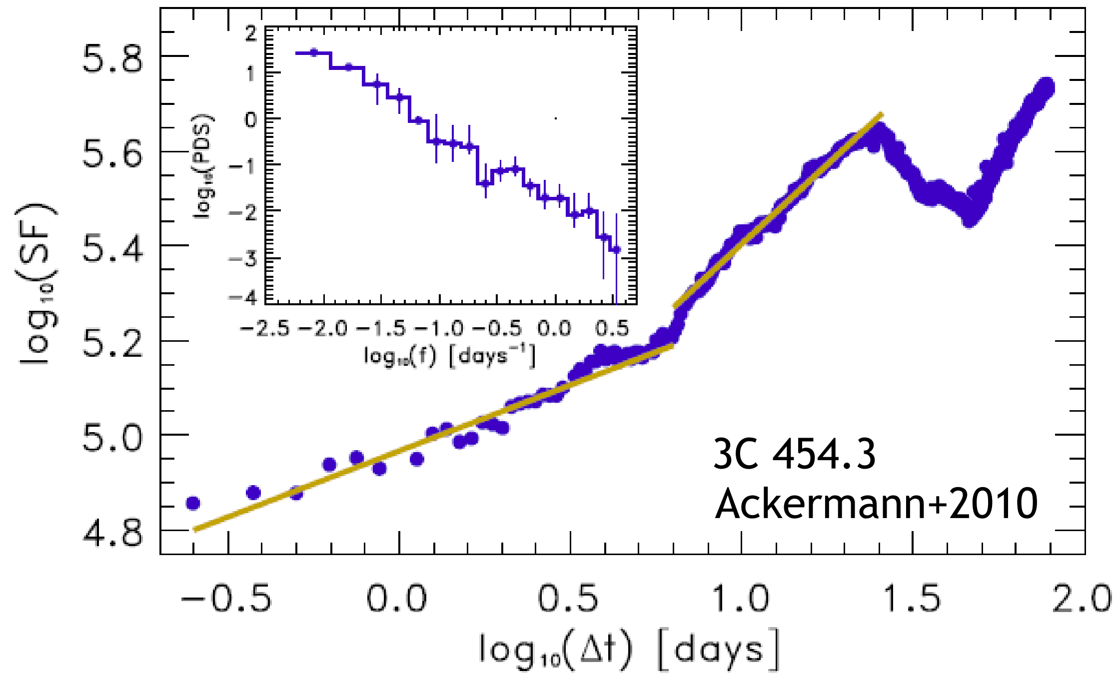
4. Can we constrain the geometry of blazar γ-ray emitting zone?

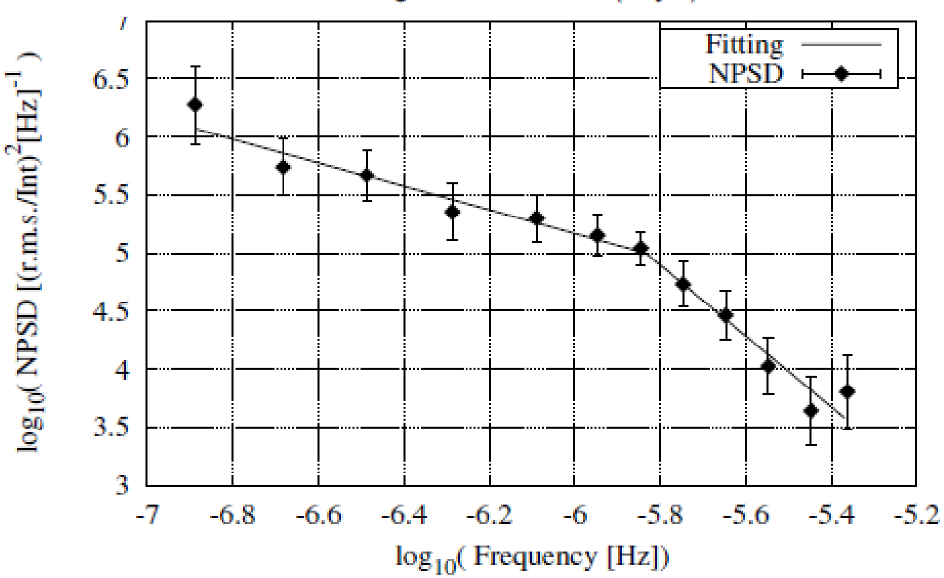
Part 2. Applications. Fermi/LAT γ-ray blazars

The first 11 months of the Fermi/LAT data



120-day flare, Fermi/LAT data
characteristic timescale at 6.5 days

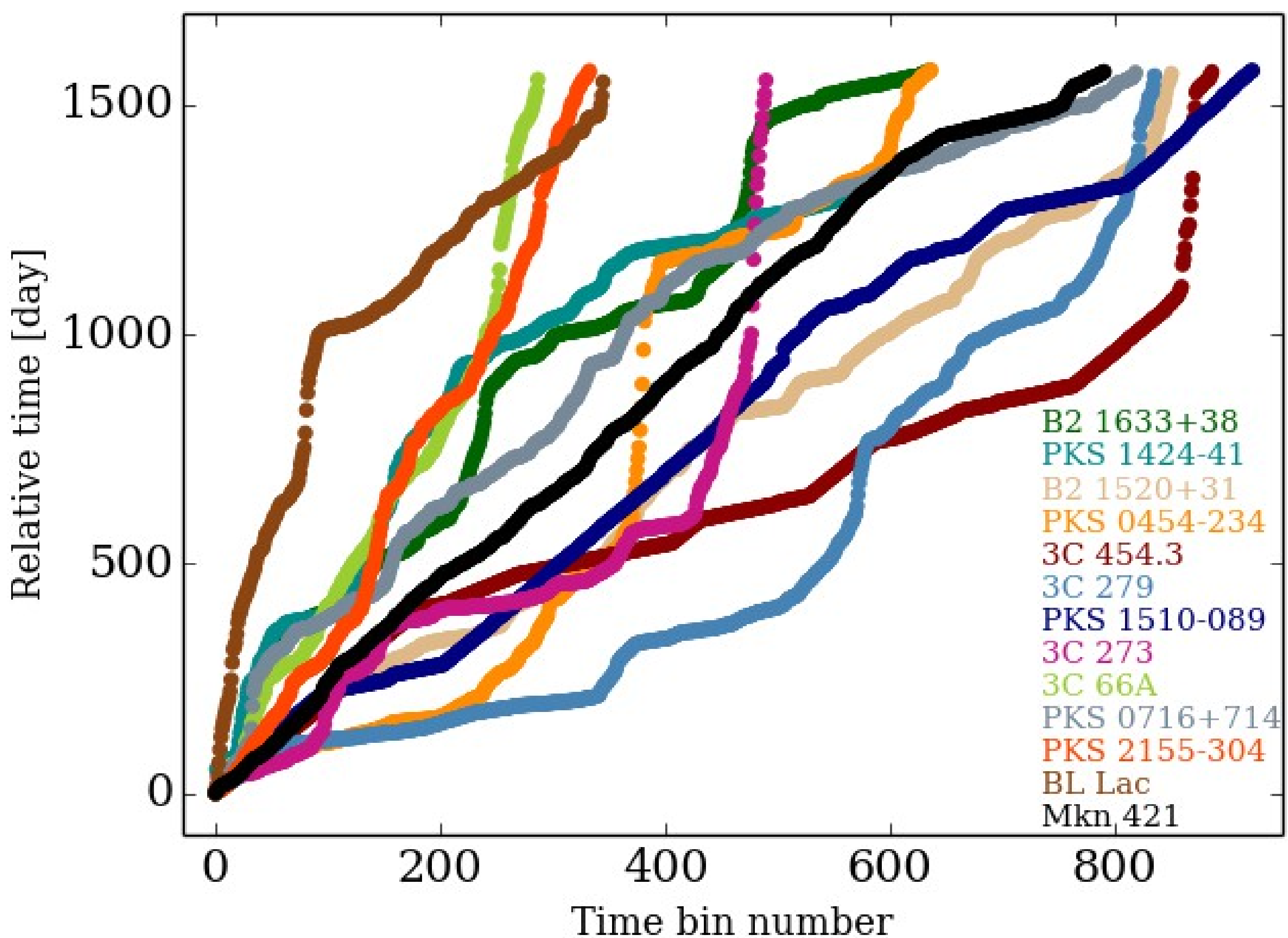




The first 4 years of the Fermi/LAT data
PSD of 15 blazars
characteristic timescale only in 3C 454.3 at ~7.5 days

Nakagawa & Mori 2013

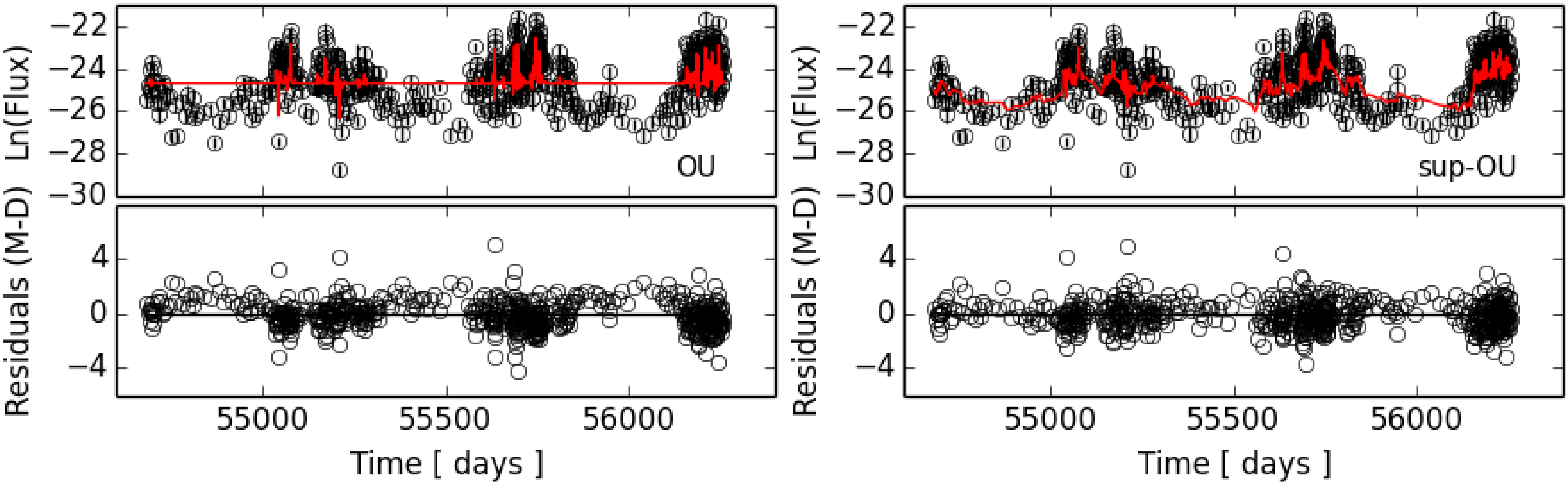
Part 2. Applications. Fermi/LAT γ-ray blazars

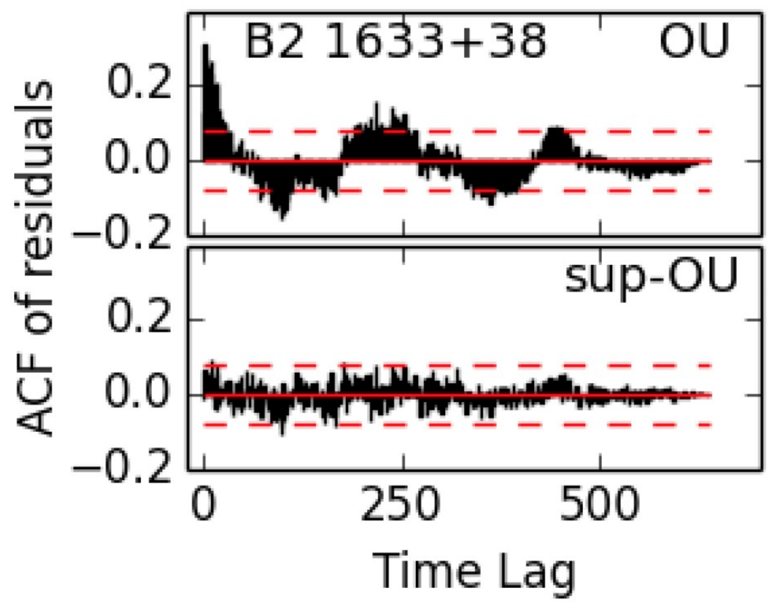


Sobolewska+2014

Part 2. Applications. Fermi/LAT γ-ray blazars

The mixed OU model favored in 10 of 13 blazars





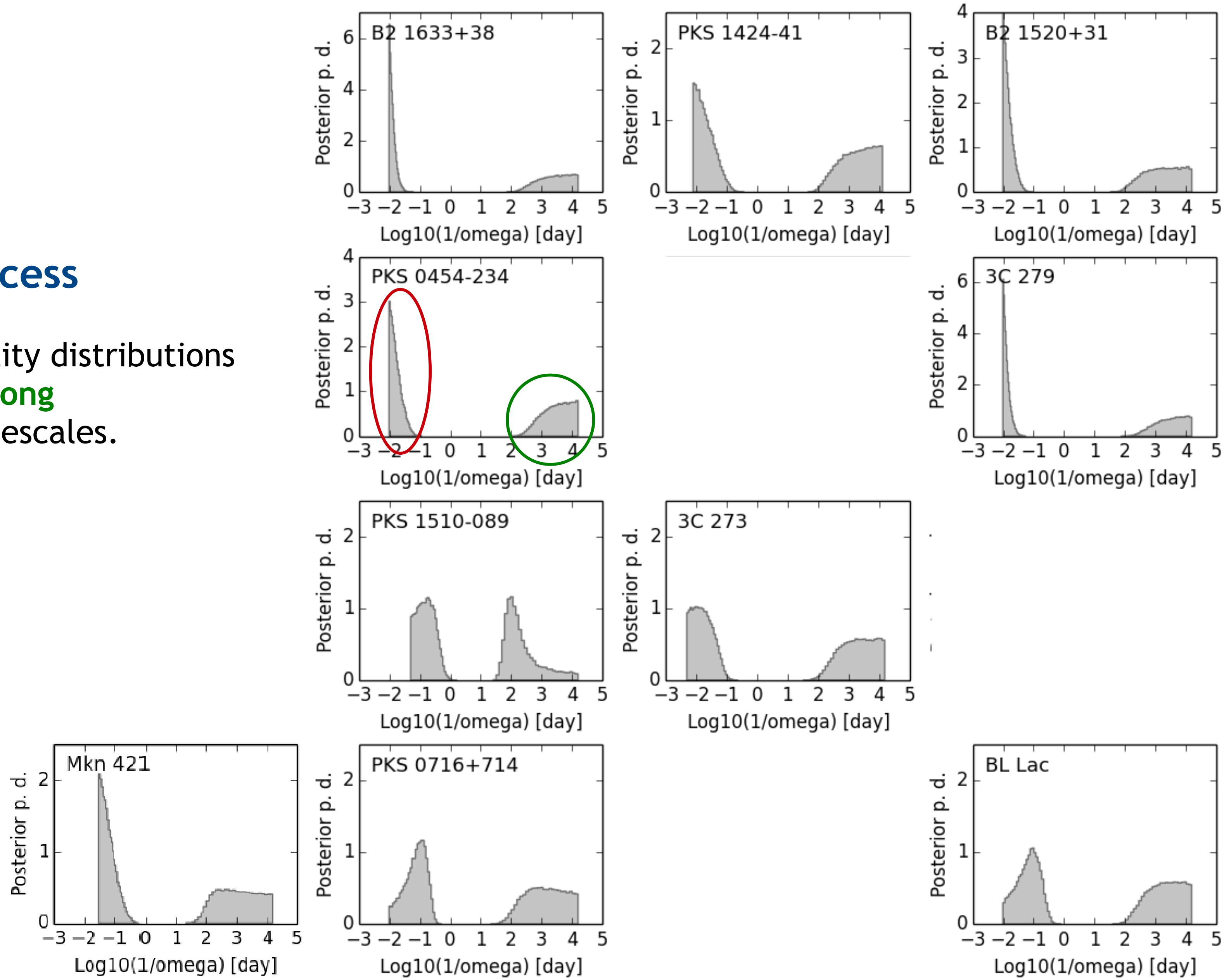
Sobolewska+2014

Part 2. Applications. Fermi/LAT γ-ray blazars

Mixed OU process

Posterior probability distributions of the short and long characteristic timescales.

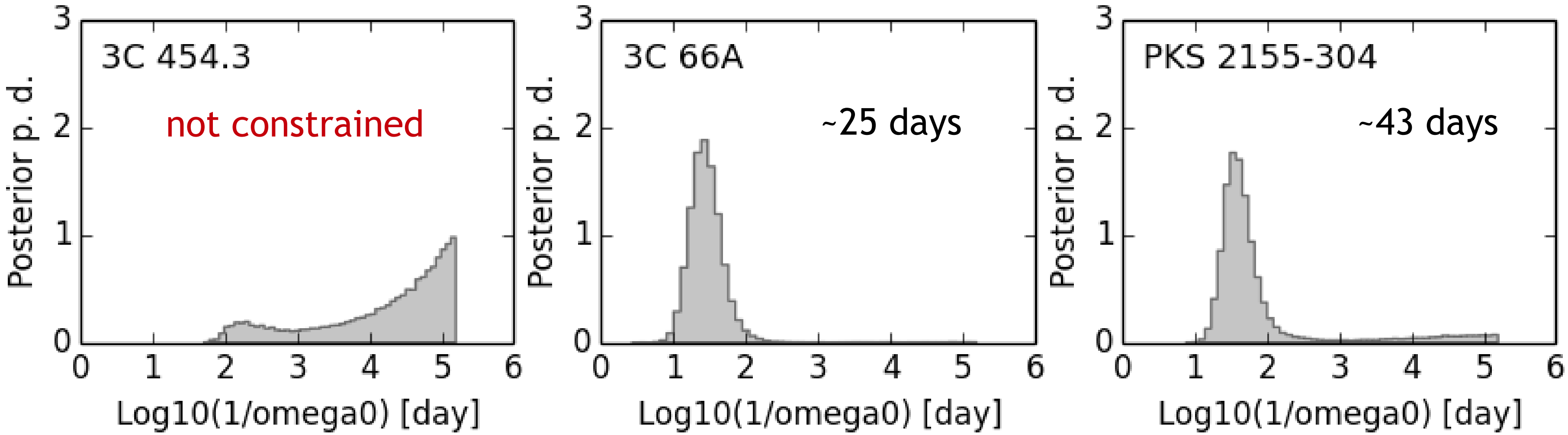
Sobolewska+2014



Part 2. Applications. Fermi/LAT γ-ray blazars

The OU model

Posterior probability distributions of the <u>OU characteristic timescale</u>



Sobolewska+2014

Summary

The Fermi/LAT γ-ray lightcurves of blazars consistent with the **OU or mixed OU processes.**

Characteristic time scales constrained in two BL Lac type sources. Limits derived for the remaining sources.

Constraints on the blazar PSD slopes.

Hints for a sub-hour scale blazar variability.

CARMA model – fast and flexible method of characterising AGN variability.

Insights into the **jet/corona** interplay (X-ray band) in 3C 273. Realistic estimate of broad band variability and its uncertainty on various time scales.

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